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Presented at the New York Academy of Sciences
International Congress of Subsonic Aeronautics

GPO PRICE $ ____________

CFSTI PRICE(S) $ ____________

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

New York, New York
April 3-6, 1967

[redacted]

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SUMMARY

This paper points out some of the fundamental characteristics of fan-powered V/STOL aircraft and demonstrates with various test data how these fundamental characteristics show up in the characteristics of various particular configurations. Since most of the experience with fan-powered V/STOL configurations has been gained in wind tunnels, the emphasis in the paper is on aerodynamics although some operational data from flight tests are presented.

INTRODUCTION

There have been several fan-powered V/STOL aircraft built and a considerably larger number of fan-powered V/STOL aircraft configurations have been tested in wind tunnels; but the experimental work has not been systematic enough, and the theoretical work has not been complete enough to permit determination of the characteristics of arbitrary configurations. The purpose of the present paper is to provide an aid for the understanding of the aerodynamic characteristics of such aircraft by pointing out some of the fundamental characteristics of such aircraft and demonstrating with various test data how these fundamental characteristics show up in the characteristics of particular configurations as observed in wind-tunnel and flight tests. Since the wind-tunnel experience is much greater than the flight experience, the main emphasis will be on characteristics observed in wind-tunnel tests.

The fundamental characteristics of fan-powered V/STOL aircraft will be discussed as they apply to the three general configurations presently under

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consideration. These three general configurations are shown in figure 1. They are: (1) the lift-fan configuration in which the fans are used only for VTOL lift and remain essentially horizontal throughout the flight range, (2) the tilting-fan configuration in which the fans tilt 90° as the transition is made from hovering to conventional forward flight, and (3) the vectored-thrust configuration in which the fans remain in the cruise-flight position at all times and their efflux is deflected downward to provide direct lift for VTOL operation. The aerodynamic and operating characteristics of such aircraft will be discussed for the hovering, transition, and cruise flight conditions. The characteristics are not discussed in quantitative terms, but rather in qualitative terms that apply to fan-powered aircraft for a wide variety of disk loadings ranging from those associated with high-pressure-ratio lift and cruise fans to those associated with ducted propellers.

HOVERING

Characteristics of Fans

One of the fundamental characteristics of ducted fans, as illustrated in figure 2, is that they experience a high drag in a side wind. This characteristic results from the fact that when such a fan moves horizontally, or is exposed to a horizontal gust, it turns the air 90° down through the fan. It therefore experiences a drag which is equal to the mass flow of air through the fan per second times the velocity of the relative wind. This drag is much greater than that of a free propeller or rotor since the air can go through the free propeller at a small angle and does not have to turn 90°. This characteristic of a high drag in side winds results in aircraft powered by such fans being more responsive to side gusts and also requiring greater tilt angles of the fan to achieve a given airspeed. If the inlet of such fans is much displaced from the center of gravity, as, for example, in the case of a configuration such as configuration 3 of figure 1, the force normal to the inlet can produce a sizable moment - for example, a yawing moment in response to a side gust for configuration 3.

Another fundamental characteristic of ducted fans, as illustrated in figure 3, is that when they are exposed to a side wind they develop large moments. These moments result mainly from the fact that the fans develop more lift on the upwind lip of the duct than on the downwind lip of the duct. The moment of a ducted fan is much greater than that of a free propeller capable of producing the same thrust per horsepower as illustrated by the test data at the bottom of figure 3. When such fans are in a horizontal position for hovering flight, as in the case of configurations such as configurations 1 and 2 of figure 1, this moment is the principal cause of unstable oscillations such as those shown in figure 4. Such an unstable oscillation was experienced in tests of free-flight models of the XV-5A and X-22A airplanes of references 1 and 2 and in the tests of other ducted fan models reported in references 3 to 7. These unstable oscillations do not seem to be troublesome in the full-scale aircraft, however, because the period of the oscillation is so long that the pilot never sees anything but the initial motion which appears as a dihedral effect.

Ground Effects

The fundamental characteristics of the exhaust flows of fan-powered VTOL aircraft in hovering flight in ground effect are shown in figure 5. These flows result in ground effects on lift and on problems related to the recirculation of the slipstream through the fans. These characteristics are not peculiar to fan-powered aircraft, but are experienced in some form with most types of VTOL aircraft. The sketch at the top of figure 5 shows that if the fan efflux exhausts near the center of the aircraft it entrains air under the aircraft as it flows outward along the ground and that this pumping of air from beneath the aircraft causes low pressure under the aircraft and consequently causes a suck-down effect on the airframe. This download results in an unfavorable ground effect on lift; and, if it is unsymmetrical, it can result in a variation of pitching moment with height above the ground. A ground-induced pitching moment was quite noticeable to pilots of the XV-5A fan-in-wing aircraft although they could easily learn to anticipate and compensate for this effect.

If the lifting fans are spread out in the airframe, the situation is that shown in the lower sketch of figure 5. The efflux of the fans tends to form an upward flowing fountain of air between the fans. If there is no airframe between the fans to prevent this upflow, the upflow forms a powerful mechanism for slipstream recirculation and the ingestion of debris by the fans. Random fluctuations in this recirculating slipstream can cause erratic aerodynamic disturbances to the aircraft when it is hovering near the ground. Such disturbances are reported in the discussion of free-flight model tests of the X-22A aircraft in reference 2. If there is a substantial amount of airframe between the fans to block the upward flow of the slipstream, this upflow causes a positive pressure beneath the airframe which results in a favorable ground effect on lift and also in pitching moments if the system is unsymmetrical. Such ground effects were experienced in full-scale flight tests of the XV-5A aircraft and in model tests of both the XV-5A and X-22A aircraft (see refs. 1 and 2). In the flight tests of the XV-5A aircraft it was noted that the ground effect from the upward-flowing column of air between the fans was quite subject to ground winds and aircraft tilt angles. It seemed that it was quite easy for the upflow to be deflected enough to get out from under the fuselage so that the favorable ground cushion effect would be lost.

The foregoing items are all effects on the aircraft. There has been much speculation over the years about the effects of the aircraft on the ground for high-disk-loading aircraft such as those powered with lift fans. This is a very difficult area for which to set up meaningful experiments, but about a year ago some real operational experience was gained with the XV-5A aircraft which is powered with fans having a pressure ratio of about 1.1, or a disk loading of about 350 pounds per square foot. The aircraft was operated from various unprepared surfaces. Perhaps the most critical tests were operation from cultivated fields and dry, hard, relatively bare desert areas. These tests showed no damage to the earth of the cultivated fields. They also showed that the dust cloud created in operation from the dry desert surface was much less dense and less extensive than had been commonly supposed. The pilot had no great difficulty in seeing sufficiently well to make take-offs and landings from the dry, dusty surface. In another test, the aircraft was operated, along with a helicopter of about the same gross weight, from a site in close proximity to tents and parked vehicles without damaging the tents or vehicles. In fact, the XV-5A lift-fan aircraft seemed to cause less disturbance to the surrounding objects than did the helicopter. This latter result is in agreement with the analysis of the problem of slipstream effects on surrounding objects presented in reference 8.

TRANSITION

The main point to be treated in the transition range is the variation of lift with forward speed. This factor is of great importance because it determines the STOL capability of the aircraft, its engine out safety, and its efficiency during protracted operation in the transition speed range as might be required by traffic procedures, particularly under instrument conditions. The variation of lift with airspeed is made up of two factors: (1) the variation of the thrust of the fans themselves, and (2) the variation of the lift induced by the fans on the airframe.

Thrust of Fans

The variation of the thrust of the fans with airspeed is illustrated in figure 6. In order to provide some orientation on the scale of velocity ratio in this and subsequent figures, it might be noted that a velocity ratio of about 0.5 represents approximately the speed at which a lift or cruise fan-powered V/STOL airplane could complete the transition and become completely wing supported. The data of figure 6 show that the thrust of a fan located deep in a duct shows the expected increase with increasing speed, but that the thrust of a fan of a fan-in-wing configuration decreases with increasing speed. This loss in thrust, as explained in reference 9, results from the fact that the pressure recovery is low and the distortion great at a station near the lip of a duct operating in a cross flow, whereas both the pressure recovery and distortion are improved farther down in the duct. Since in a fan-in-wing configuration, the fan must be near the lip of the duct, its performance suffers from low pressure recovery and high distortion; whereas, when the fan is located far down in the duct, it has greater thrust because of the improved conditions under which it operates. This effect of the proximity of the face of the fan to the lip of the inlet is not peculiar to lift fans; it has also been observed in relation to inlets for lifting turbojet engines as noted in reference 10. Recently some tests have been run in the Ames 40- by 80-foot tunnel in which boundary-layer control was applied to the inlet of a lift fan in an attempt to improve the inlet performance and thereby prevent the loss in thrust with increasing speed shown in figure 6 for the fan-in-wing configuration. These data have not been completely worked up or analyzed, but they show that the use of BLC on the forward lip of the inlet significantly increased the thrust of the fan in the transition speed range - even when allowance was made for the engine bleed air required for BLC.

Lift Induced on Airframe

The foregoing discussion deals with the characteristics of the fan itself. Now, however, let us examine the effect of the fan on the surrounding airframe. This is a much more complicated subject. First, the flow field induced by the fans will be illustrated; and then it will be shown that the effects of chordwise location of the fans are just those that would be expected from this flow field for a wide variety of fan-powered configurations. Next, the drag of the fans will be discussed, and the effects on lift of vectoring the fan exhaust will be illustrated. And, finally, it will be shown that the span of the powered-lift system has a major effect on the efficiency of flight in the transition range just as the span of a wing does in conventional cruising flight.

Flow field induced by fan.- Figure 7 shows the effect of a lift fan on the airflow around it. The fan is a lifting system and has all the normal effects of any lifting system in forward flight. It creates an upwash ahead of the fan and a downwash behind it. The downwash created behind the wing, or fan fairing, causes a download on any surface behind the wing. The upwash ahead of the fan causes lift on the portion of the wing, or fairing, ahead of the fan. It also creates a download on the upper surface of the wing immediately behind the fan and causes a download on the entire lower surface behind the fan. This type of induced load on the wing is shown by the experimentally determined pressure distribution at the bottom of figure 7, which was taken from reference 11. The next four figures (figs. 8 to 11) will show the lift characteristics of several representative fan-powered V/STOL configurations to show that they vary with configuration as might be expected on the basis of the type of airflow pattern shown in figure 7. All of these data are for the case in which the airframe is at 0° angle of attack with flap up and the fan efflux is at right angles to the airstream.

Effect of chordwise location of fans on lift.- The effects of the foregoing type of flow and pressure distribution are shown in figure 8 for a configuration with a fold-out lift fan located in a fairing ahead of the wing. These data were taken from reference 12. This figure shows the variation of the lift of the fan, the fairing, and the wing with forward speed. The data show a reduction in fan thrust with increasing speed such as that illustrated for a fan-in-wing configuration in connection with figure 6. The data also show that there is a large induced lift on the fairing around the fan. They also show that the downwash from the fan causes a considerable download on the wing behind the fan so that the total lift is considerably less than that of the fan and fairing. It should be noted that lift on the fairing is lift in addition to the familiar suction on the lip of the duct of the ducted fan. This lift on the lip of the duct was measured as part of the fan thrust since the fan thrust was measured by pressure survey of the fan exit. This induced lift on the fairing is to be expected from the upwash induced by the fan and can be calculated by the theory of reference 9. This theory is quite useful in analyzing the performance of lift-fan configurations. It is not, however, the kind of theory in which the uninitiated can insert numbers and get the correct answer. The use of this theory requires experience and background with lift-fan aerodynamics for successful application. Nevertheless, it is a very useful tool for extrapolation of data by the properly skilled aerodynamicist.

Figure 9 shows the effect of the fan-induced flow (that is, of the type of flow discussed in connection with fig. 7) on the lift of fan-in-wing configurations with the fans located at various positions in the wing root. The effects are different, depending on the chordwise location of the fans as might be expected from the flow field described in figure 7. With the fans located in the front position there is a loss in lift with increasing airspeed because of the large area behind the fans on which the suction pressures on the lower surface can act. With the fans in the rear location there is a decided increase in lift with increasing airspeed because of the large area ahead of the fan on which the fan-induced upwash can cause lift. In this rear position, the fan is acting in the same manner as a jet flap (see ref. 13). With both the front and rear rans, there is a smaller increase in lift with increasing speed. The data for these three configurations were taken from reference 12 which summarizes the characteristics of such configurations in more detail. The data of figure 9 also show that with a fan in a midchord position there is a small increase in lift with increasing airspeed indicating that for such a configuration the fan-induced upload on the forward part of the wing is greater than the combined losses due to the download on the rear of the wing and the reduction in fan thrust with increasing speed.

Additional data illustrating the effect of the chordwise position of the fans in the wing are presented in figure 10 for a quite different configuration. This configuration has six fans spread along the span of the wing, and the inboard and center fans could be located at either of two chordwise stations. The data show that the increase of lift with increasing forward speed was significantly greater when the fans were in the rearward position than when they were in the forward position.

The same type of result is shown in figure 11 for another quite different configuration - an integrated fan-wing configuration in which the fan efflux is exhausted through a slot nozzle across the entire span of the wing. The model was tested with the fan efflux nozzle at various chordwise positions, two of which are shown in the figure. In all cases there was a thin jet sheet of air exhausted on the upper surface of the wing and turned downward around the trailing edge of the wing. The data of figure 11 show that with the fan efflux nozzle at the trailing edge of the wing, there was a large increase in lift with increasing airspeed. There was, however, a large nose-down pitching moment which might be difficult to trim. This pitching-moment problem is the reason for interest in the more forward fan exit locations which would not be expected to give as much induced lift on the wing. The data for the forward fan nozzle location shows the expected result. The pitching moment is almost zero, but there is a smaller increase in lift with increasing airspeed. The data of figures 8 to 11 therefore show the type of aerodynamic results that would be expected on the basis of the flow pattern induced by the fan, which is shown in figure 7.

Effect of drag of fans on lift.- The drag characteristics of lift fans are illustrated in figure 12 which shows a large increase in drag with increasing airspeed. This is an extension of the characteristic of high drag in side winds brought out in connection with hovering flight. The drag data at the bottom of the figure were taken from reference 9 for a fan-in-wing configuration. They show that, with 0° vectoring of the fan exhaust, the drag increases rapidly with increasing airspeed. This drag can be calculated fairly accurately by the expression

$$D = mV$$

which assumes that the airflow is turned 90° to flow directly along the fan axis as it goes through the fan. The data of figure 12 also show that the fan efflux can be vectored by louvers beneath the fan to produce zero drag over the entire transition speed range. This vectoring causes some loss in lift, however, as might be suspected.

Figure 13 shows the variation of lift with airspeed for the conditions of zero thrust vectoring and for the case vectoring to give zero drag, or zero longitudinal acceleration. These data show that the increase in lift with increasing airspeed is considerably lower for the case in which the fan exhaust was vectored for drag trim. This loss in lift with exhaust vectoring is the result largely of two factors: (1) a loss in the vertical component of fan thrust, and (2) a reduced fan-induced lift on the wing. This reduction in fan-induced lift on the wing is the result that would be expected from jet-flap aerodynamic theory (ref. 13).

Effect of span on efficiency.- So far in this discussion the illustrations have been given in terms of the lift that can be produced with a given power, actually with a given fan rotational speed. Sometimes it is helpful, however, to look at the problem the other way around; that is, in terms of the power, or thrust, required to produce a given lift.

The effect of span on the efficiency of flight in the transition speed range is illustrated in figures 14 and 15. Figure 14 shows the variation of thrust required with airspeed as calculated by the classical induced drag equation

$$T_{req'd} = \frac{{C_L}^2}{\pi A}$$

More exact thrust-required curves, and ones which would converge on $T_{req'd}/W = 1.0$ at $V = 0$, can be calculated easily from the nomograph of reference 14. The foregoing induced drag relation is used herein, however, in order to illustrate the effect of span in terms familiar to the airplane aerodynamicist. Curves are shown for two aspect ratios to illustrate the well-known fact that more thrust is required to fly with a low-aspect-ratio configuration than with a high-aspect-ratio configuration - particularly at low speeds, or high-lift coefficients. It was first pointed out in reference 15 that this is true for cases in which lift is produced by power just as it is for conventional wing-borne flight. This reference paper points out that because of this fact it is desirable to have the lift due to thrust spread out as widely and as uniformly as possible across as large a span as possible in order to achieve high lifting efficiency or high STOL capability in the transition speed range. Figure 15 shows an illustration of this point.

Figure 15 shows how several fan-powered V/STOL configurations fit in with this concept of the importance of the span of the powered lift system. The calculated induced-thrust-required curves from figure 14 are repeated for reference, and test data are shown for four different configurations. Two of these configurations are fan-in-wing configurations and have aspect ratio 3.5 wings with a ratio of total fan area to wing area of about 0.10. In one case two large fans are located in the wing roots (configuration 1 of ref. 11); whereas, in the other case, six smaller fans are spread across the entire span of the wing. (These latter data have not yet been published.) A third configuration is a jet-flap configuration in which the fan efflux is spread in a jet sheet uniformly along the entire trailing edge of the wing; the thrust-required curve for this configuration is based on experimental data from reference 13. The fourth configuration is the deflected-slipstream configuration of reference 16 where the efflux from four discrete fans is spread across the entire span at the trailing edge of the wing by an application of the external flow jet-flap principle of reference 13 to give an approximation of the uniform sheet jet flap. The ratio of total fan area to wing area for this configuration is about the same as that for the fan-in-wing configurations - 0.10. Both of the jet-flap configurations have wings of aspect ratio 7.0. All of the data shown are for flaps-down conditions; and the flap angles or fan louver angles are those required for $D = 0$, or zero longitudinal acceleration, at each airspeed. The thrust-required values are for gross thrust, that is, the momentum of the fan efflux. In this respect the data for the deflected-slipstream configuration are different from those of reference 16 where the data in figure 6 of that reference are for net thrust required.

Figure 15 is a very "busy" figure and illustrates a number of points some of which relate directly to the original purpose of showing the importance of the span of the powered lift system and some of which do not. First, it shows that the thrust-required curves for the aspect ratio 7.0 configurations, which are also the deflected-slipstream and jet-flap configurations, are much lower than those of the aspect ratio 3.5 configurations, which are the fan-in-wing configurations. The data also show the importance of having the powered lift spread evenly across the span, since the six-fan configuration requires less thrust than the two-fan configuration for flight at a given airspeed; and the jet-flap configuration requires less thrust than the deflected-slipstream configuration. The data of figure 15 also show that the thrust-required curves for the jet-flap and deflected-slipstream configurations are of the same general magnitude as the calculated induced-thrust-required curves, whereas those for the fan-in-wing configurations are much higher than the calculated induced-thrust-required curves. The fact that the experimental data for the fan-in-wing configurations are so much higher than the induced-thrust-required curve can probably be attributed to two factors: (1) the fact that there is only a small part of the wing ahead of the fans where they can induce lift on it as compared with the case of the entire wing being ahead of the downwardly directed jet sheet for the two configurations at the bottom of figure 15, and (2) possibly due to internal losses in the fan caused by vectoring the fan thrust for forward propulsion. One final point that might be made in the way of explanation of figure 15 is that the fact that the test data for the jet-flap configuration are below the calculated value can be attributed to the thrust recovery phenomenon which is discussed in reference 13.

Stability

The last two points to be made for the transition speed range deal with stability and trim. Figure 16 shows the variation of pitching moment with airspeed in the transition speed range for several fan-powered V/STOL configurations. These data show that the deflected-slipstream configuration has a very large nose-down pitching moment such as that normally associated with jet-flap configurations. This characteristic is a serious drawback to this configuration and should be corrected by changes in configuration from that used in reference 16. The data for the two fan-in-wing configurations show the increase in nose-up pitching moment with increasing airspeed which is typical of such configurations. This characteristic results principally from three sources:

(1) the pitching moment of the ducted fan itself which was discussed in connection with figure 3, (2) the suction pressures induced by the fan on the lower surface of the wing behind the fan, and (3) the lift induced by the fan on the forward part of the wing. The lift-plus-cruise-fan configuration had relatively small variations of pitching moment with speed because the thrust and vectoring of the forward and rearward fans could be controlled separately to provide forward propulsion and, at the same time, trim out the pitching moments.

Figure 17 shows that all three of the sample configurations were directionally unstable at low airspeeds. This characteristic may not be fundamental to all fan-powered configurations, but it is fundamental to configurations such as the deflected-slipstream configuration where the fan inlets are all ahead of the center of gravity. When such an aircraft is sideslipped, the sideslip causes a lateral force at the inlet in the same manner that forward speed causes drag at the inlet of a fan such as that shown in figure 12. This lateral force due to sideslip applied ahead of the center of gravity causes the configuration to be directionally unstable until the airspeed becomes sufficiently high for the stabilizing contribution of the tail to offset the destabilizing effect of the forward fan inlets.

CRUISE

Aircraft powered by high-disk-loading lift fans or cruise fans are not expected to have any special problems in conventional wing-borne flight conditions since in this condition they have been converted to effectively conventional aircraft. Aircraft powered by lower disk loading fans which are in effect ducted propellers will have some special characteristics or problems in cruise flight, however, as a result of the characteristics of their fans - as illustrated in the following paragraphs.

Performance

Figure 18 illustrates the problem of higher-than-normal induced drag for tandem-fan configurations which results from configuration features required by considerations of longitudinal stability and trim. For such tandem configurations, the center of gravity must be located about midway between the forward and rearward ducts from considerations of pitch trim in hovering flight. When the center of gravity is in this position, about one-half the lift in cruising flight must be carried on the forward ducts which have a short span. This characteristic of supporting one-half the lift on a short span results in a low overall span efficiency factor for the aircraft - the value for the representative configuration shown in figure 18 being 0.65 as compared with values of about 0.80 for conventional aircraft configurations. This higher-than-normal induced drag is a direct cause of lower cruise flight efficiency. The data of figure 18 were taken from reference 17.

Another cause of low efficiency in cruising flight is that the efficiency of ducted propellers is inherently lower than that of conventional free propellers because the drag of the ducts and center-body support struts is higher than the drag of a wing to produce the same lift. If this extra drag is charged to the propulsive efficiency of the ducted propeller the situation is about that shown in figure 19. This figure indicates that the propeller itself would have an efficiency of about 90 percent, even though it is somewhat oversized to produce the lift required for VTOL operation. The extra drag which results from the otherwise unneeded surfaces of the duct and struts, however, corresponds to a reduction in propulsive efficiency of about 15 percent. The resultant effective propulsive efficiency of the ducted propeller for a VTOL aircraft is probably no higher than about 75 percent as compared with a value of about 85 percent for a free propeller that would produce the same static thrust with the same horsepower.

Stability

One additional problem caused by ducted propellers in cruise flight, as illustrated in figure 20, is that the ducts, because of their vertical lifting surfaces, cause an unusually high lateral force as a result of sideslip. In fact for the representative configurations shown in figure 20, the slope of the lateral force versus sideslip curve is about 1/3 the slope of the lift curve as compared with a value of about 1/20 of the slope of the lift curve for a conventional airplane. (The data for the ducted fan configuration were taken from ref. 17.) The high value of the lateral force parameter of the ducted fan configuration means that the aircraft would experience lateral accelerations due to side gusts about one-half as great as the normal accelerations due to vertical gusts. Because of the lower tolerance of the pilot to lateral acceleration this characteristic would be expected to make the riding characteristics of such an aircraft seem very rough in gusty side winds.

CONCLUDING REMARKS

A number of different points have been brought out in this paper, but probably the most significant ones are:

1. The effects of a hovering fan-powered V/STOL aircraft on things on the ground, and the related dust and debris problems, have not been nearly as severe as had been widely supposed on the basis of the slipstream velocity.

Such an aircraft has operated from many different unprepared areas with no more disturbance and no greater problems than a helicopter of equal gross weight.

2. A fan-powered lift system in the transition speed range influences the surrounding air in the same manner as any other lifting system and its general effects can consequently be anticipated on the basis of conventional aerodynamic considerations. Two of the most important of these considerations are that the powered lift system should be spread as uniformly and as far spanwise as possible for efficient flight in the transition speed range, and that the lift induced by the fans is greater when their efflux is directed downward at a more rearward chordwise station.

SYMBOLS

A	wing aspect ratio
b	wing span, ft
$\bar{c}$	wing mean aerodynamic chord, ft
D	drag, lb; or fan diameter, ft
D_e	fan effective diameter, diameter of a single fan having the same area as the total area of all fans of a configuration
e	span efficiency factor, $\frac{C_L^2/C_D}{\pi A}$
L	lift, lb
m	fan mass flow, slugs/sec
M	pitching moment, ft-lb
q	free-stream dynamic pressure, lb/ft^2
S	wing area, ft^2
T	ducted fan gross thrust, lb $\left(T = mV_j\right)$
T_s	ducted fan static thrust, lb
V	free-stream velocity, ft/sec except where otherwise noted
V_j	ducted fan exhaust velocity, ft/sec
W	aircraft weight, lb
α	angle of attack, deg
β	deflection of louvers, deg (see fig. 12)
η	propulsive efficiency
C_D	drag coefficient, $\frac{D}{qS}$
C_L	lift coefficient, $\frac{L}{qS}$
x/c	wing chordwise station/wing chord

C_n	yawing-moment coefficient, $\frac{\text{Yawing moment}}{qSb}$
C_Y	lateral-force coefficient, $\frac{\text{Lateral force}}{qS}$
C_p	pressure coefficient
C_{L_α}	lift-curve slope
C_{n_β}	directional stability parameter, $\frac{\partial C_n}{\partial \beta}$
C_{Y_β}	lateral force stability parameter, $\frac{\partial C_Y}{\partial \beta}$

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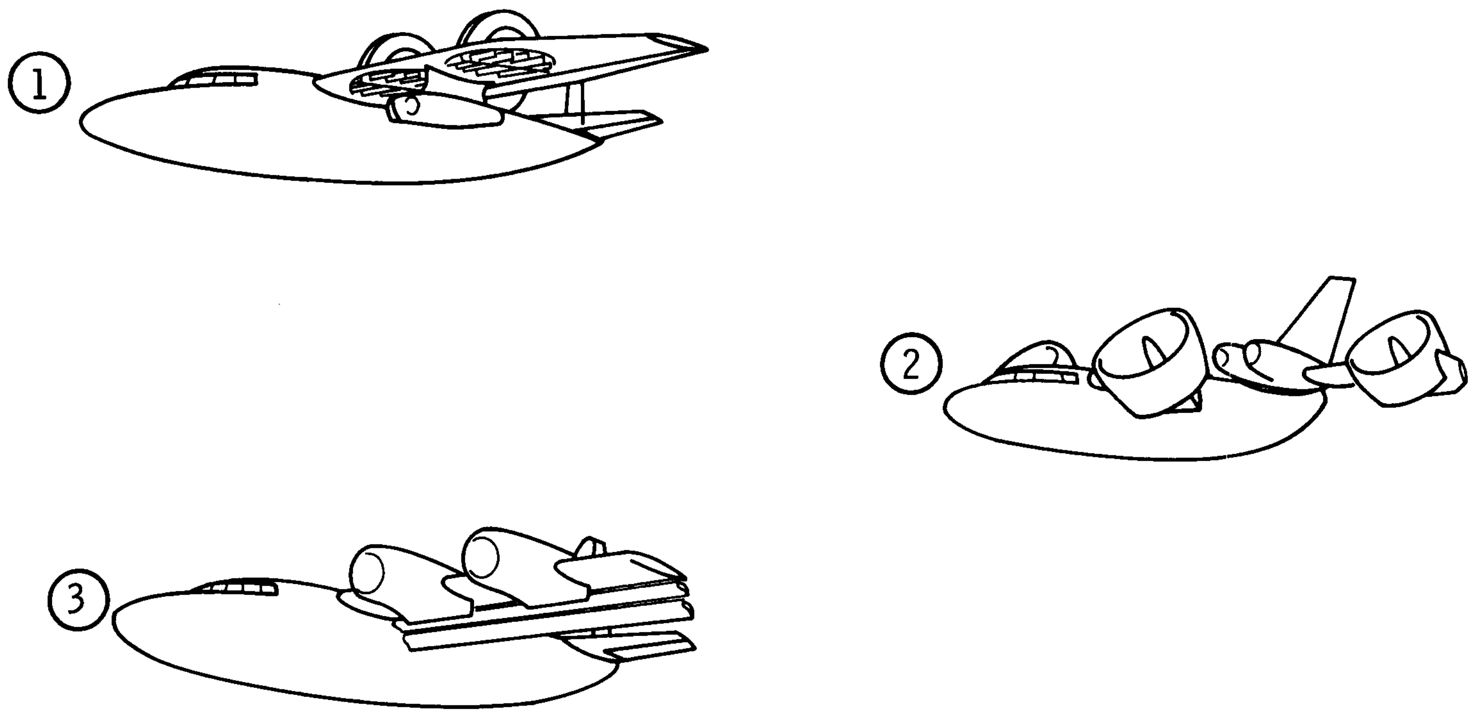

Figure 1.- Fan-powered V/STOL configurations.

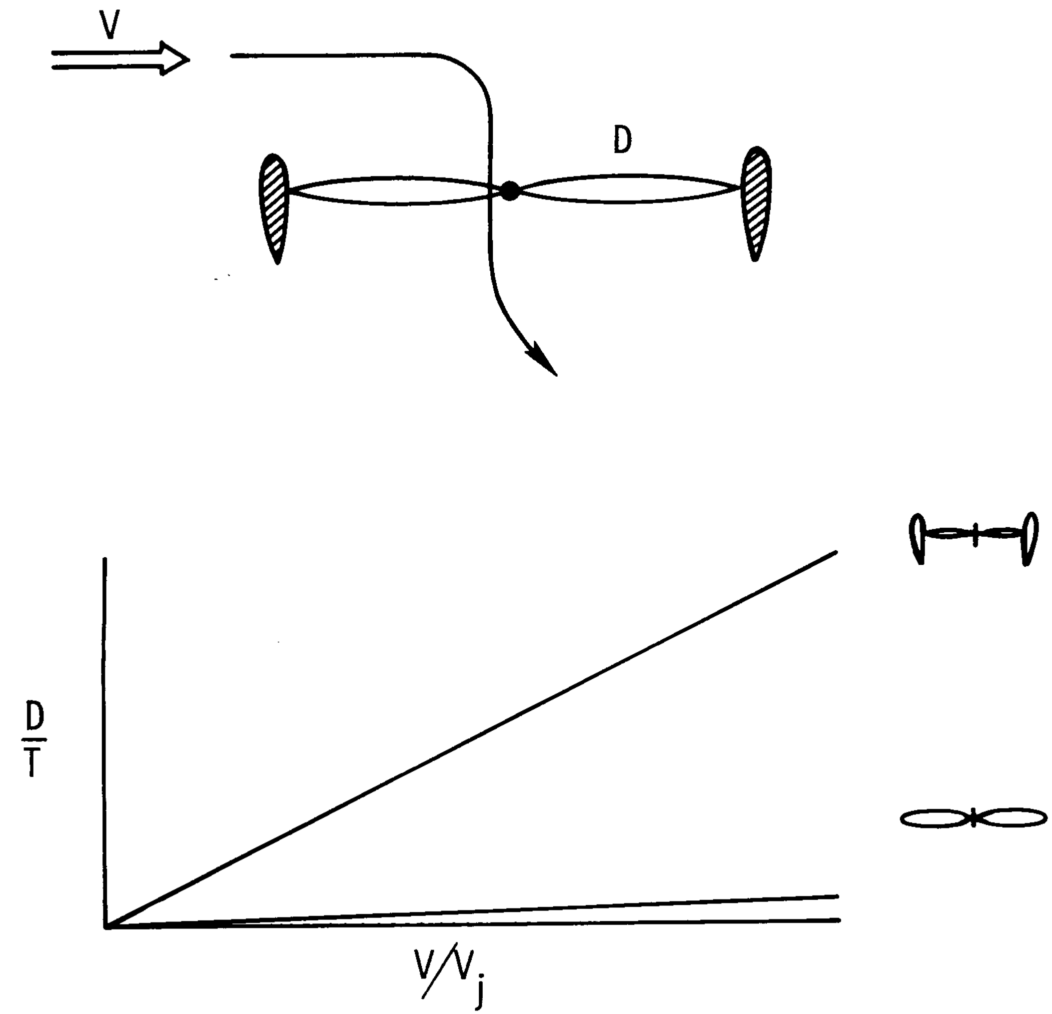

Figure 2.- Drag of ducted fan in side wind.

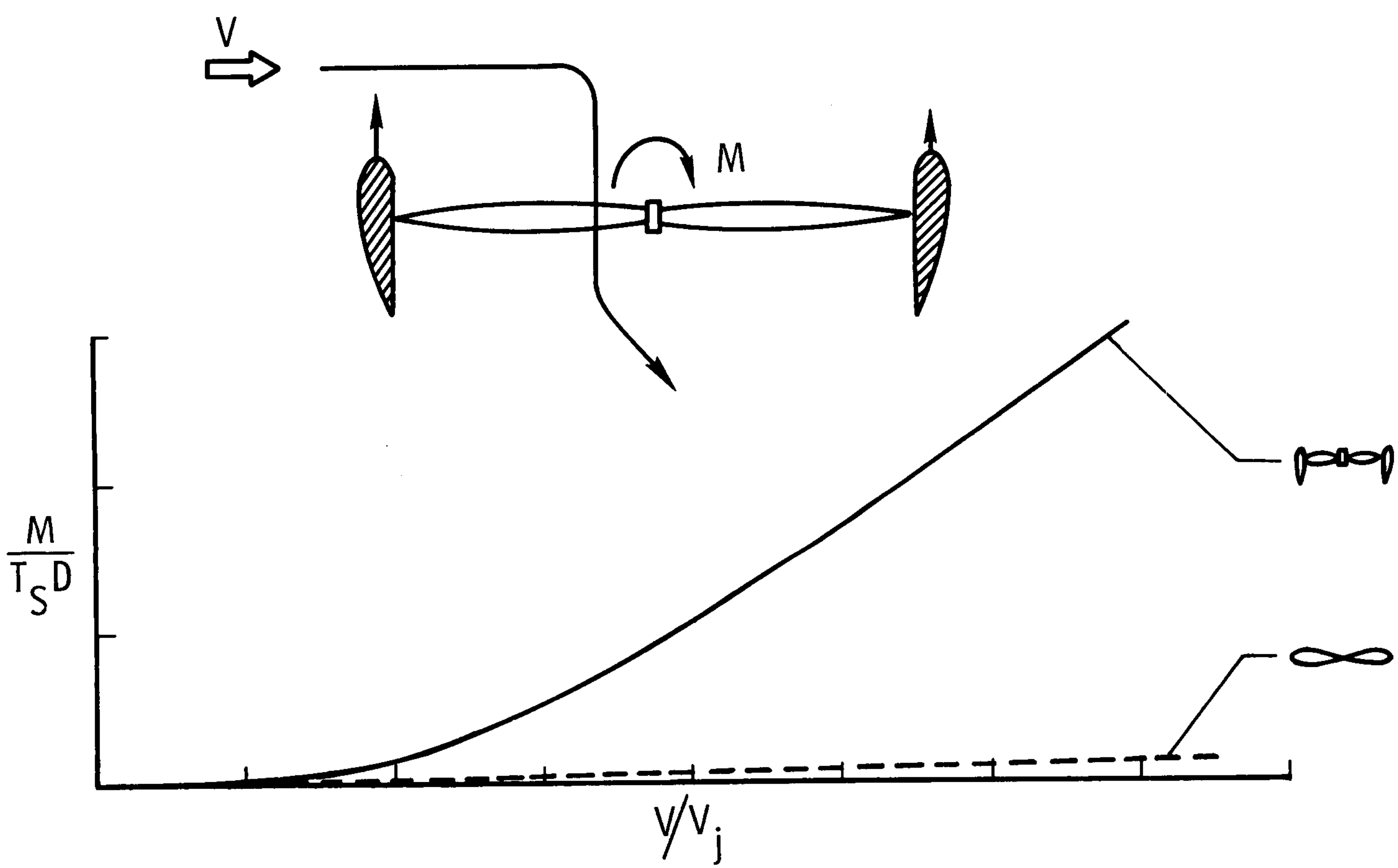

Figure 3.- Moment of ducted fan in side wind.

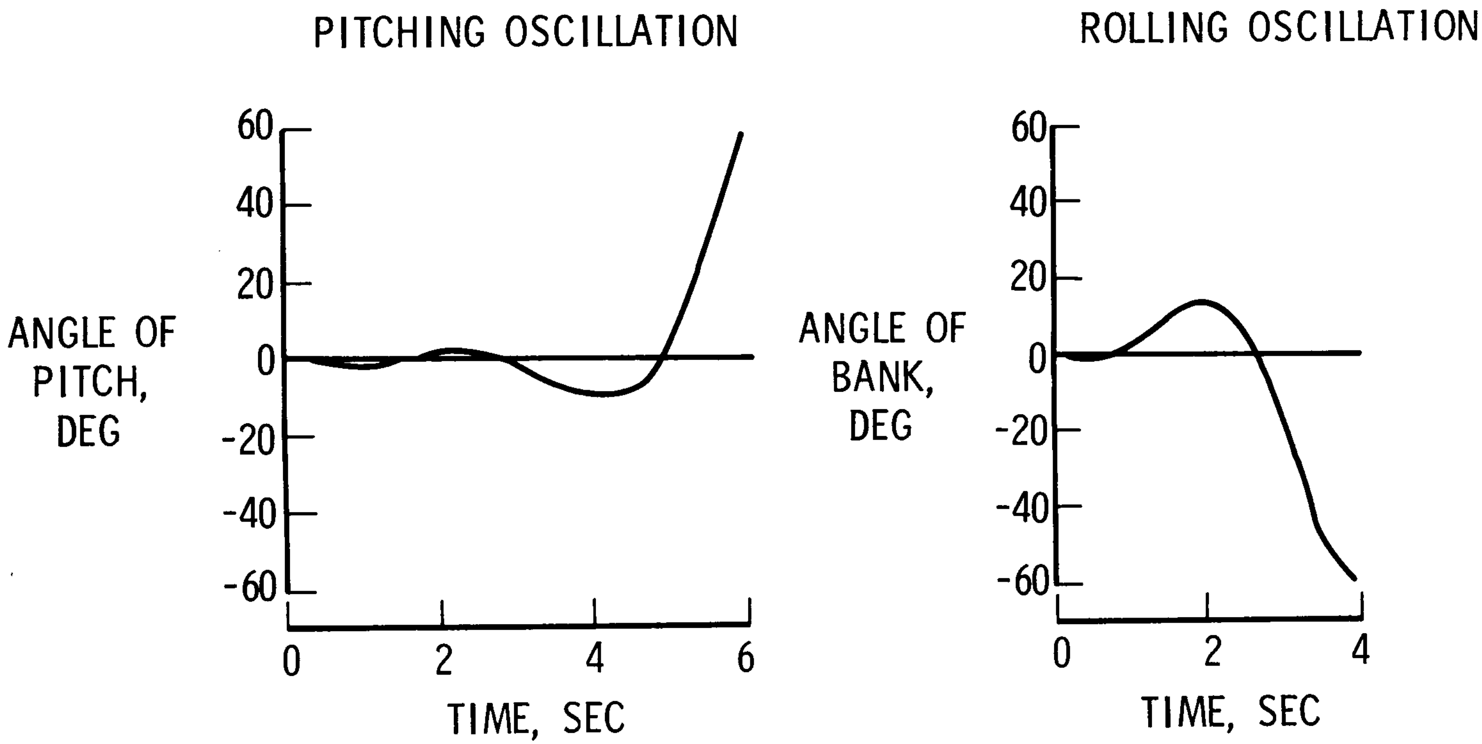

Figure 4.- Aircraft oscillations caused by duct moment.

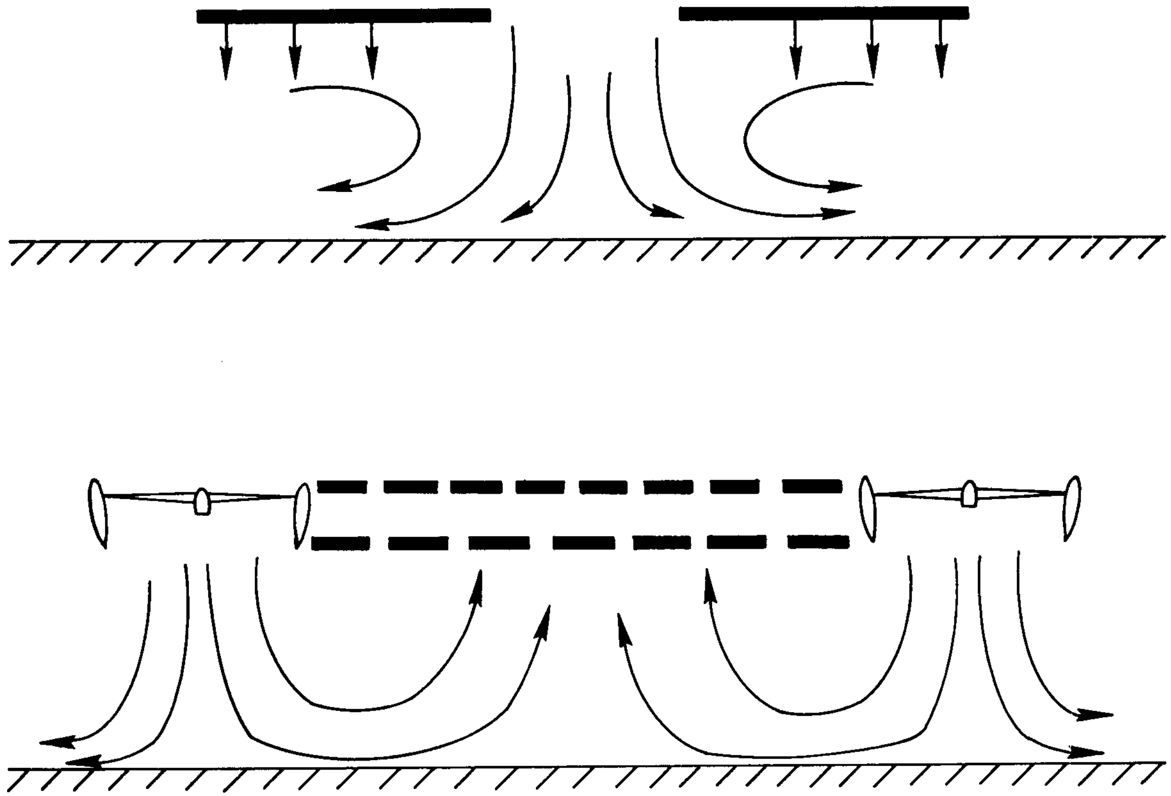

Figure 5.- Recirculation of slipstream in ground effect.

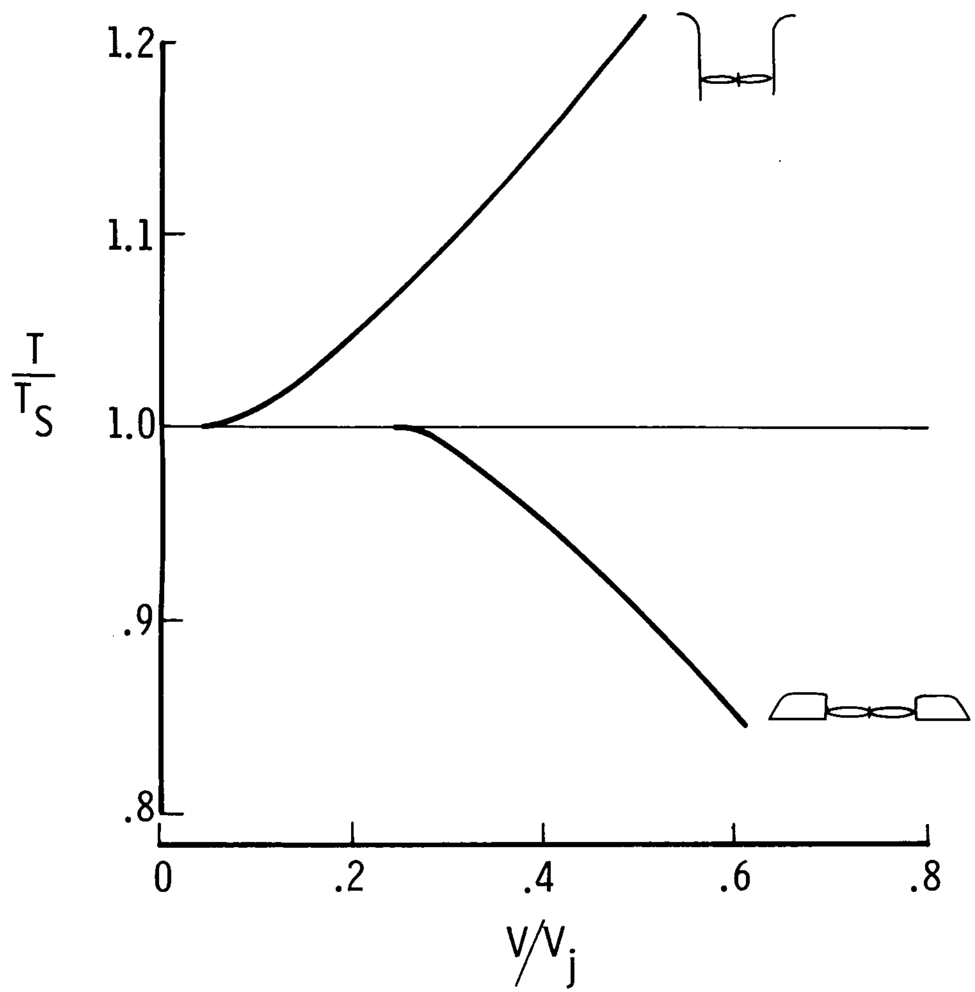

Figure 6.- Variation of lift-fan thrust with forward speed.

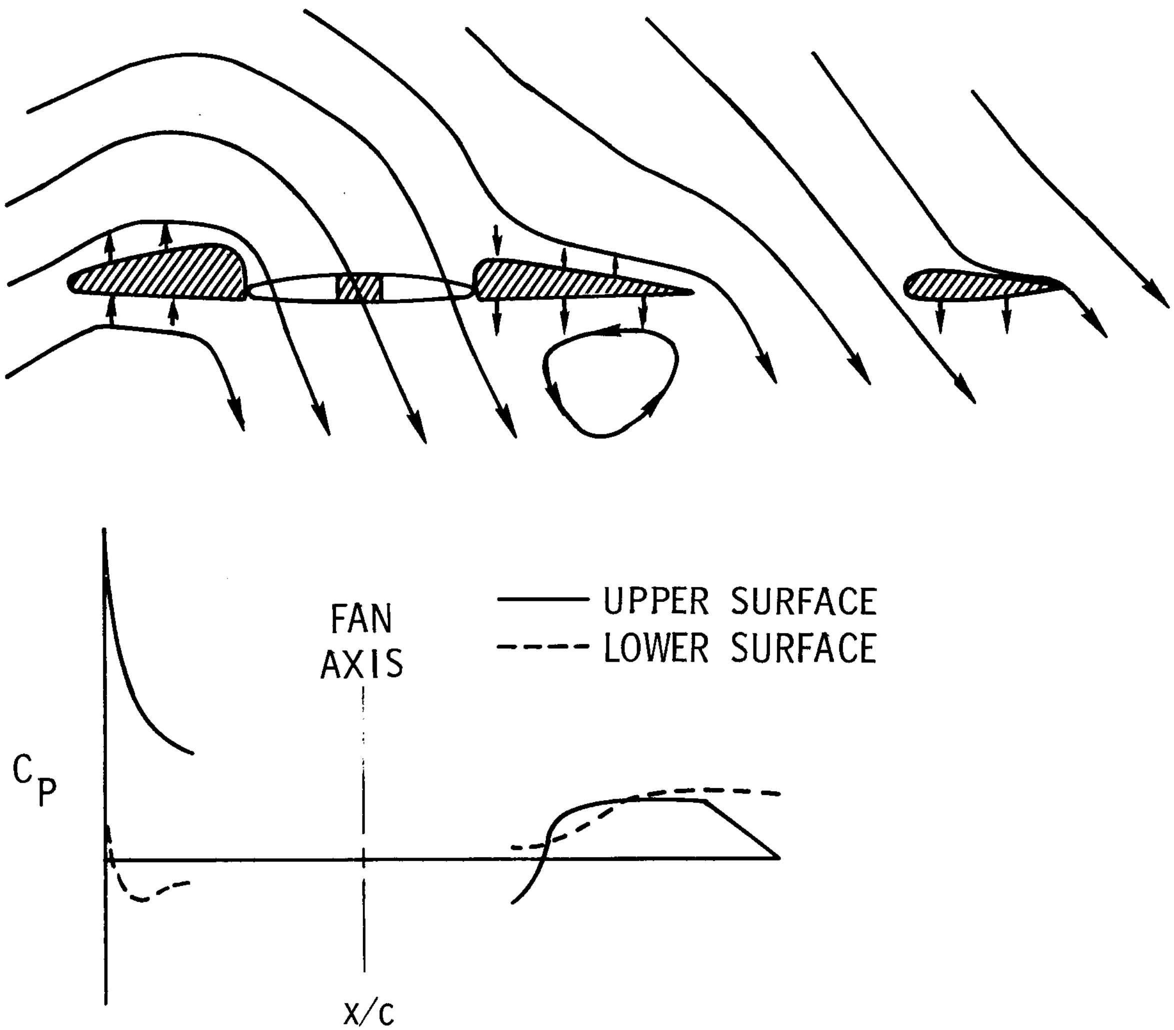

Figure 7.- Flow field and pressures induced by a lift fan.

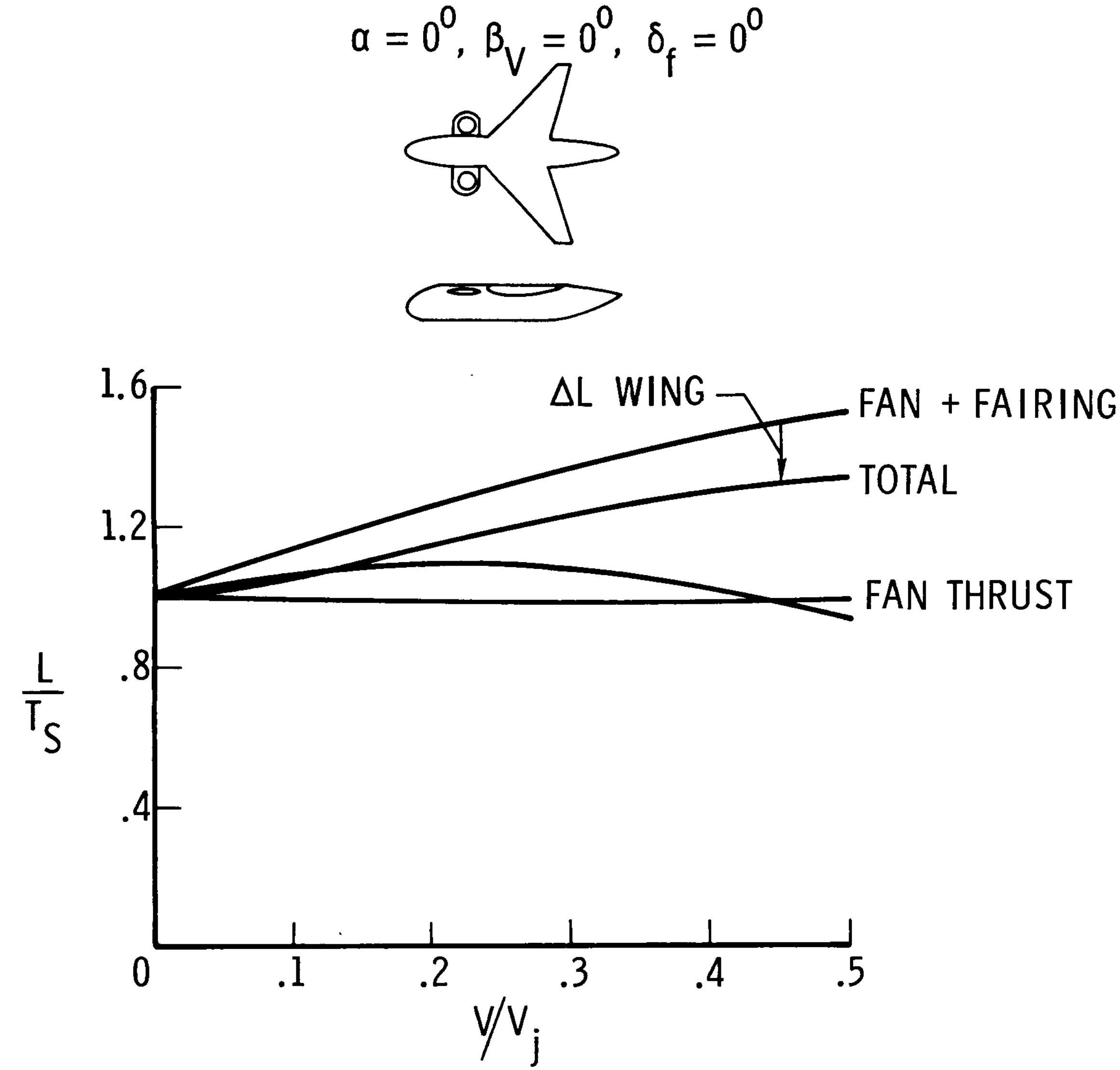

Figure 8.- Effect of lift fan ahead of wing.

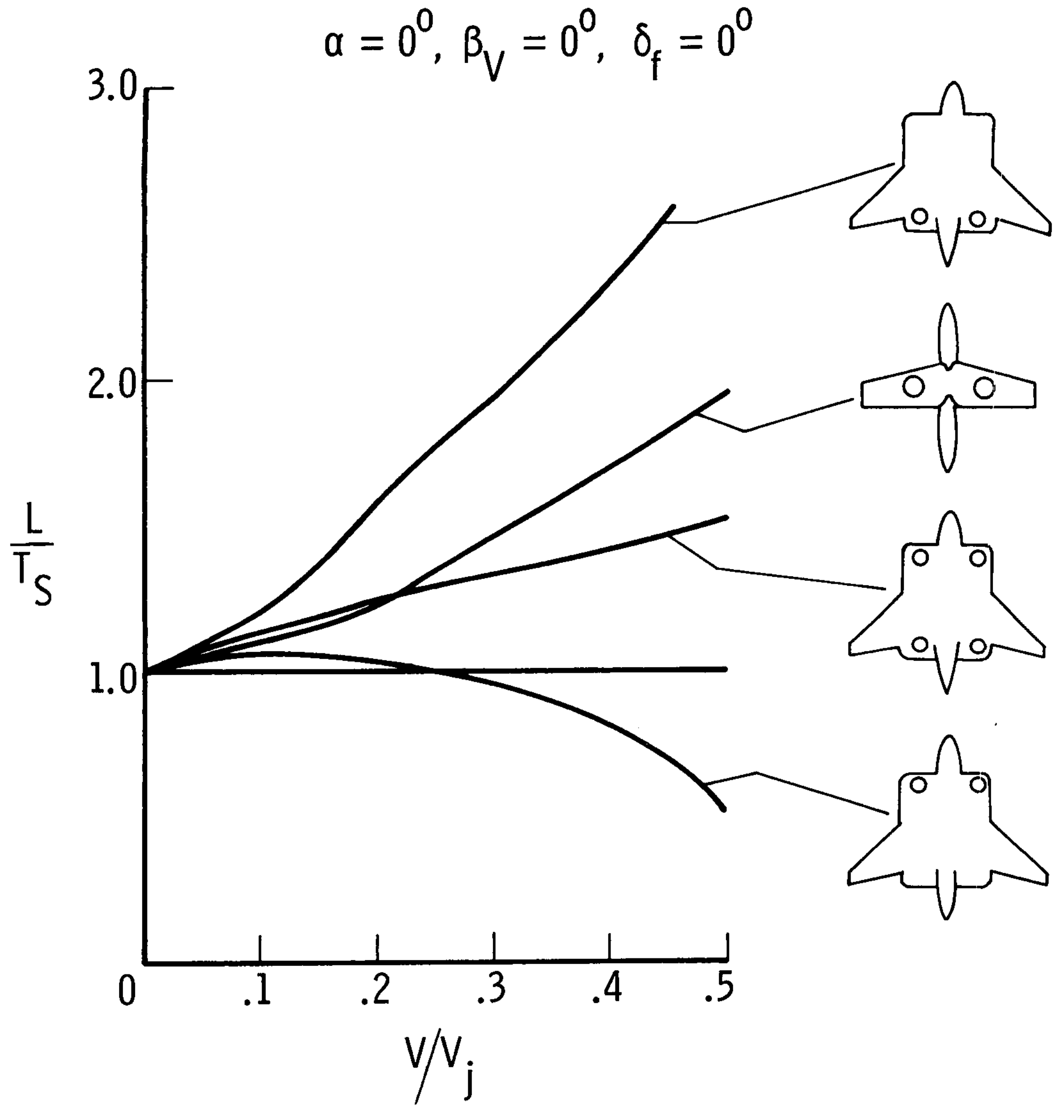

Figure 9.- Effect of chordwise location of fans in wing root.

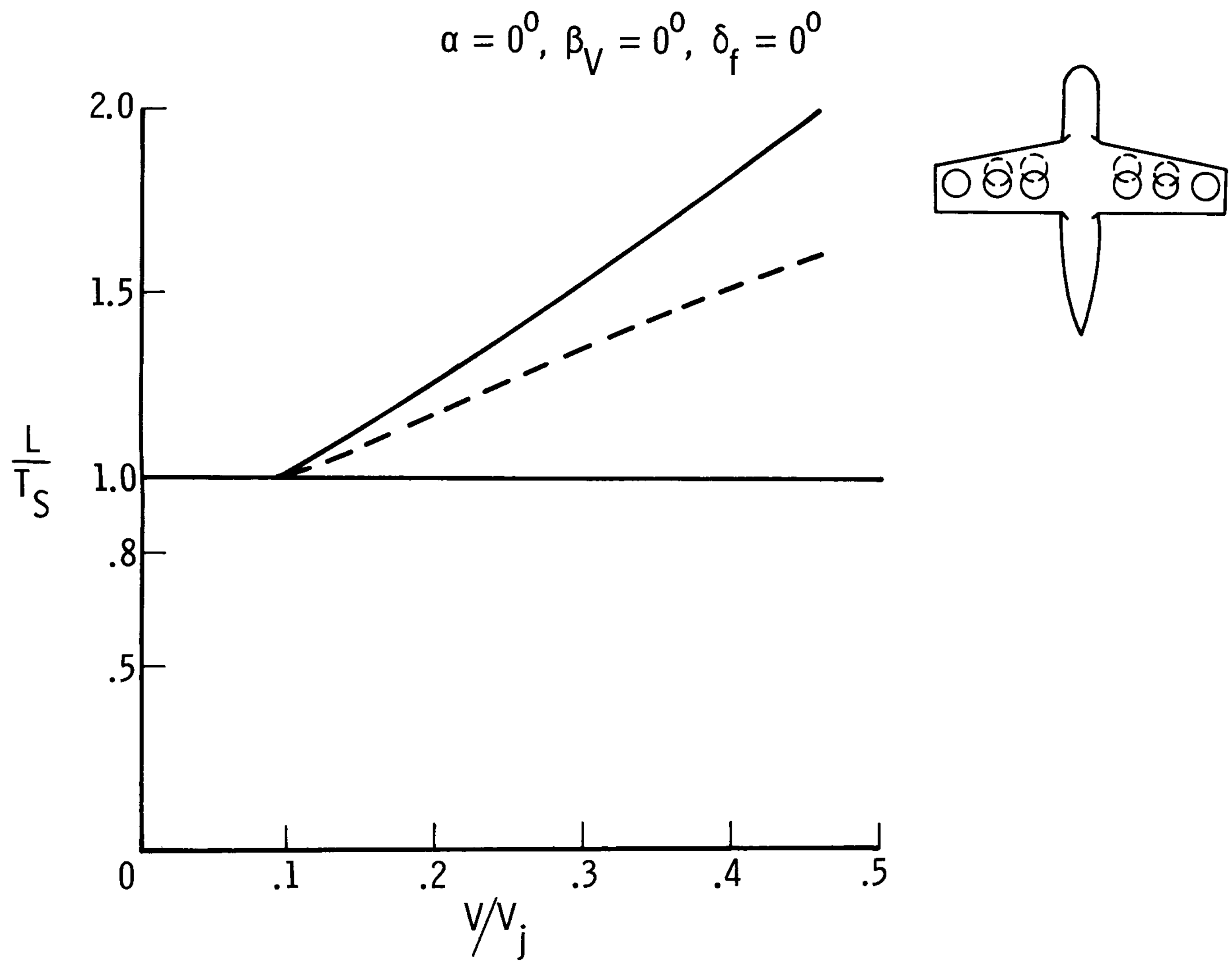

Figure 10.- Effect of chordwise location of fans.

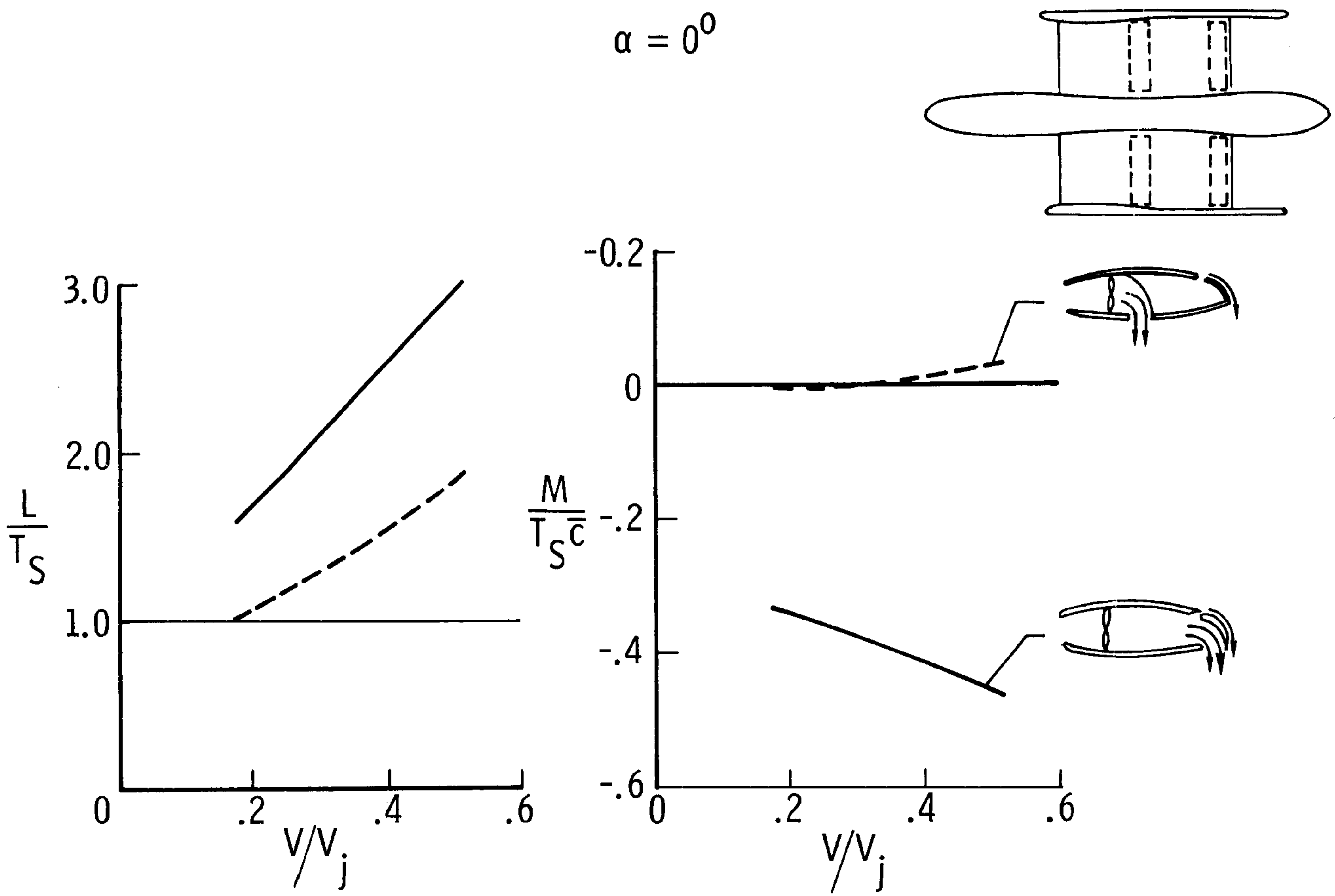

Figure 11.- Effect of chordwise position of slot nozzle.

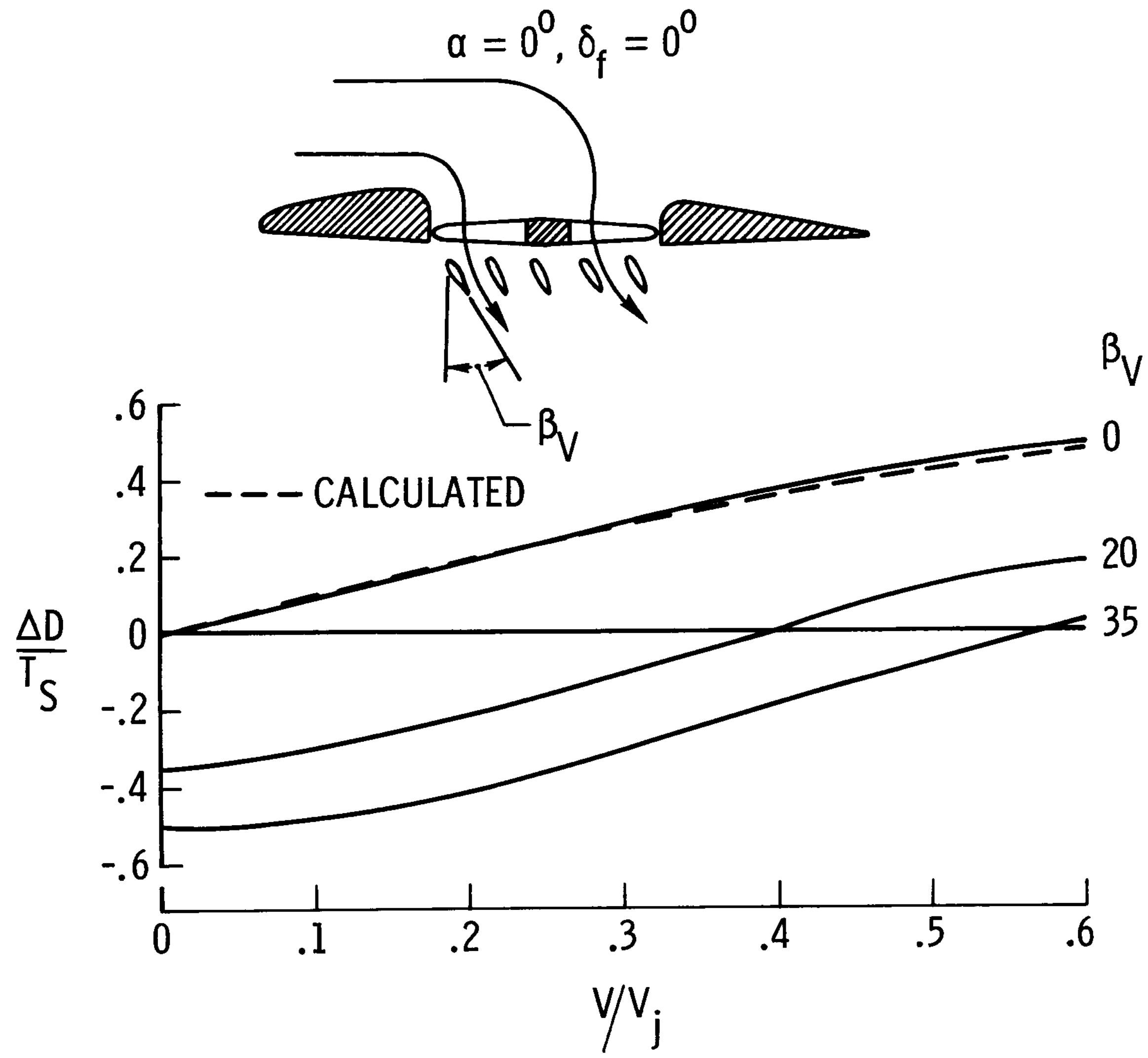

Figure 12.- Drag of lift fan in transition.

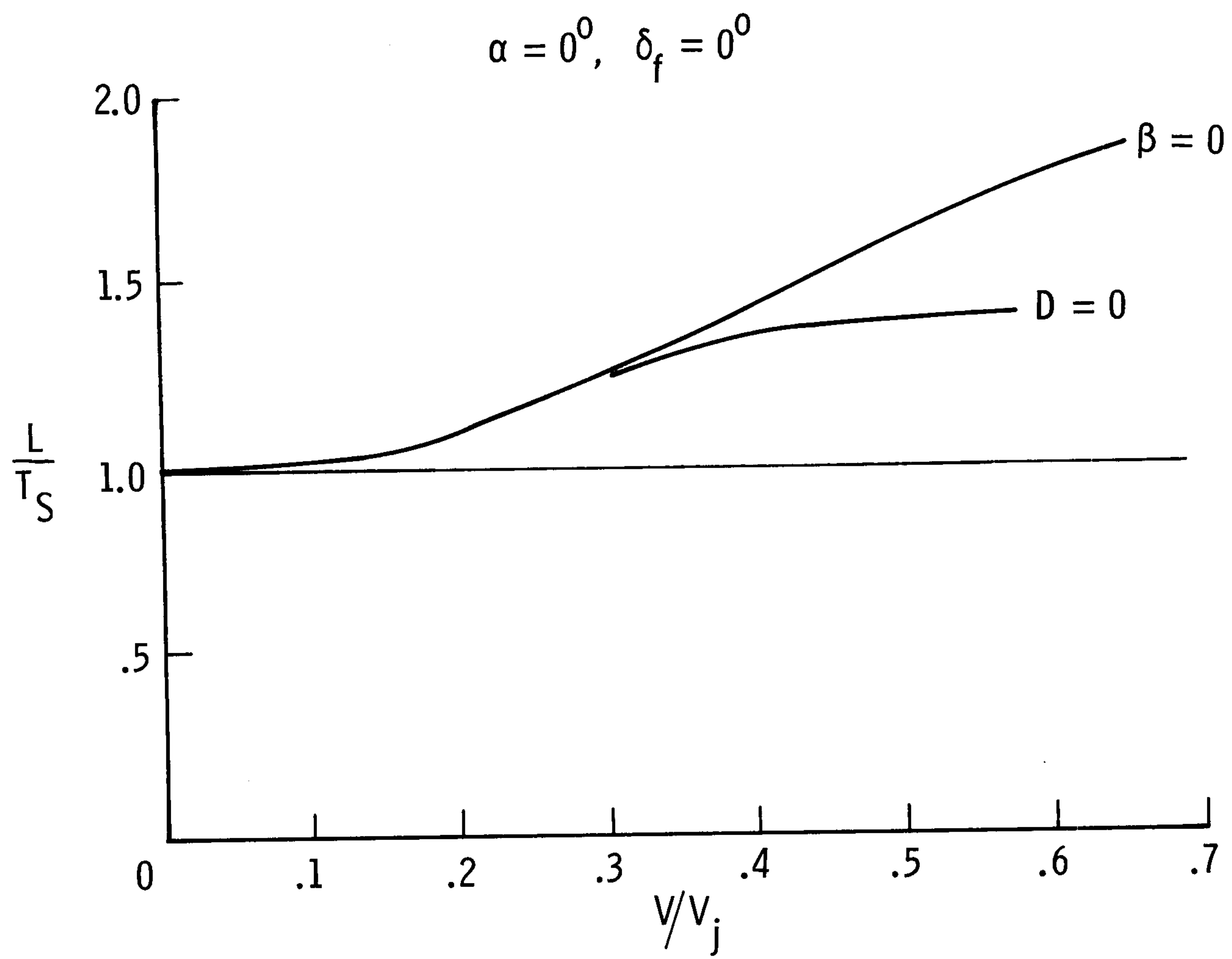

Figure 13.- Effect of fan efflux vectoring.

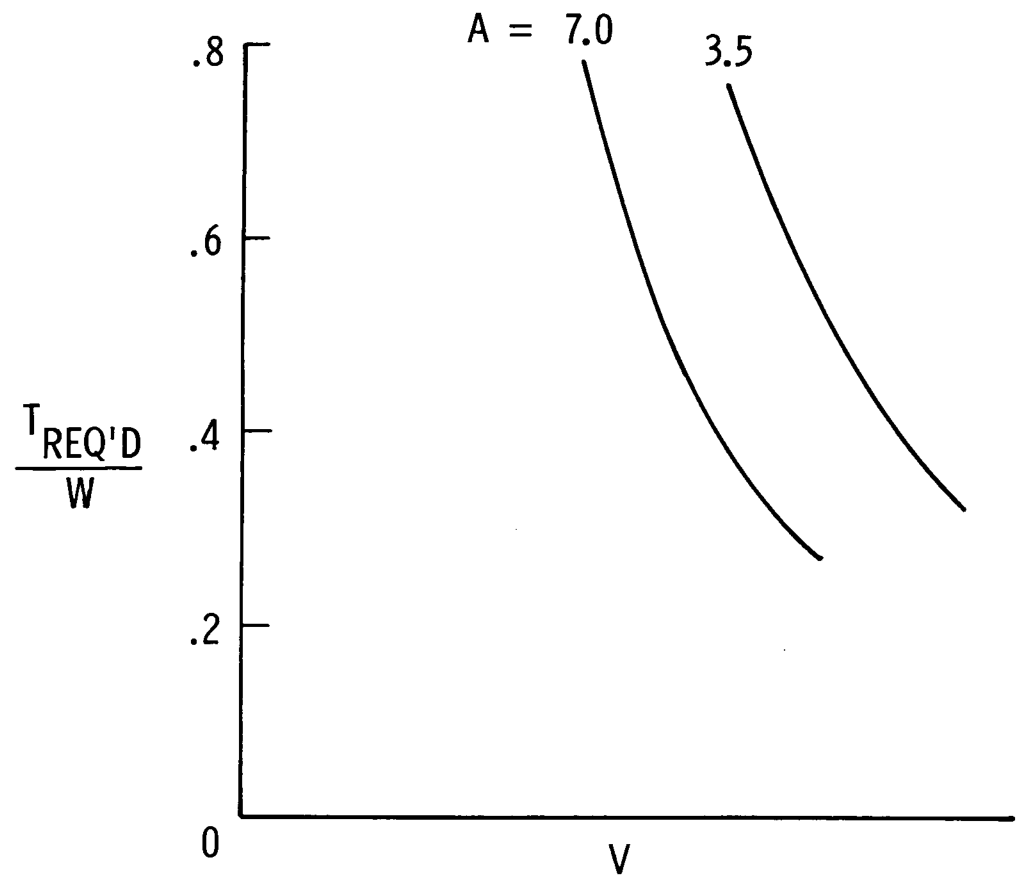

Figure 14.- Effect of aspect ratio on thrust required.

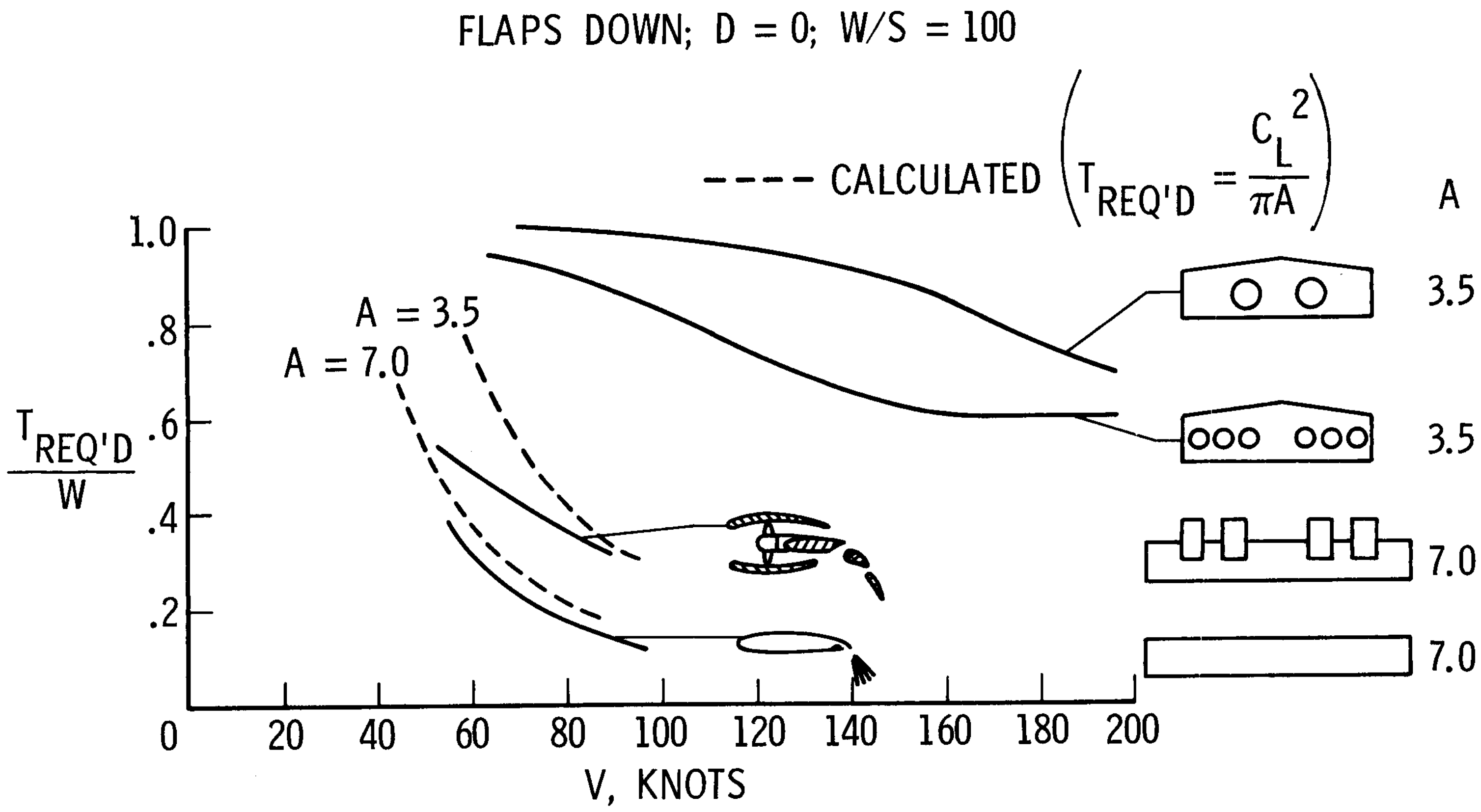

Figure 15.- Effect of aspect ratio.

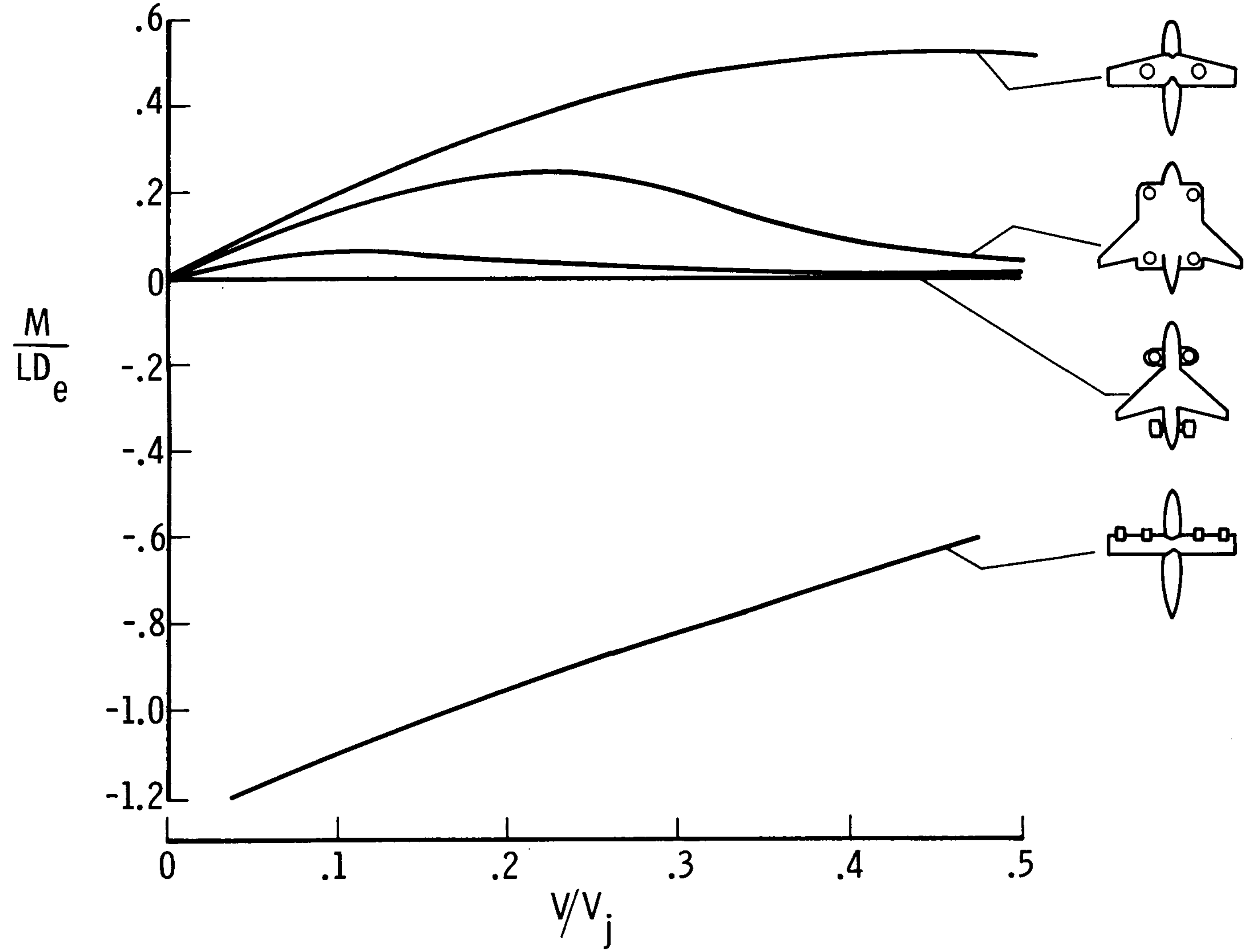

Figure 16.- Pitching moments in transition.

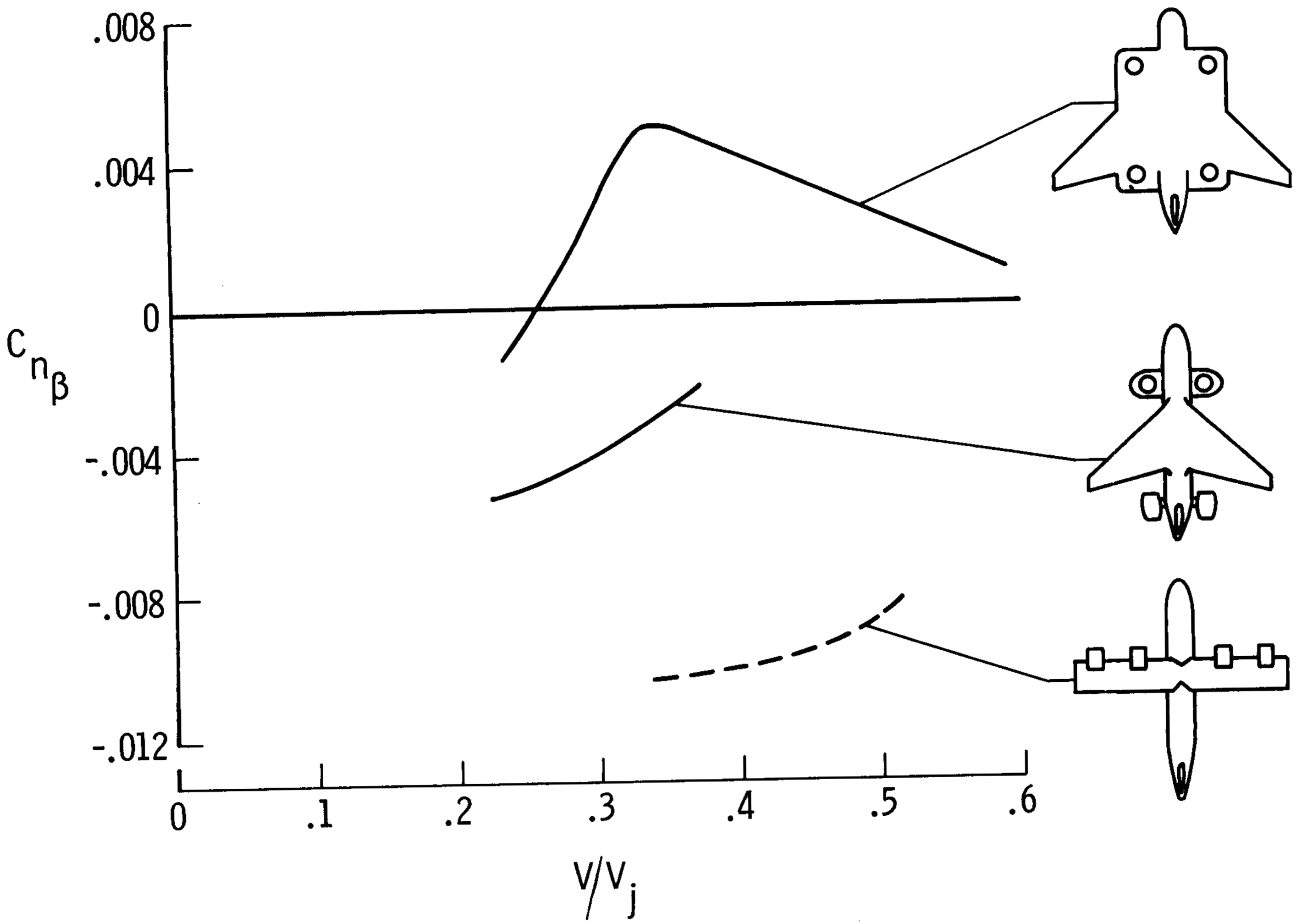

Figure 17.- Directional stability.

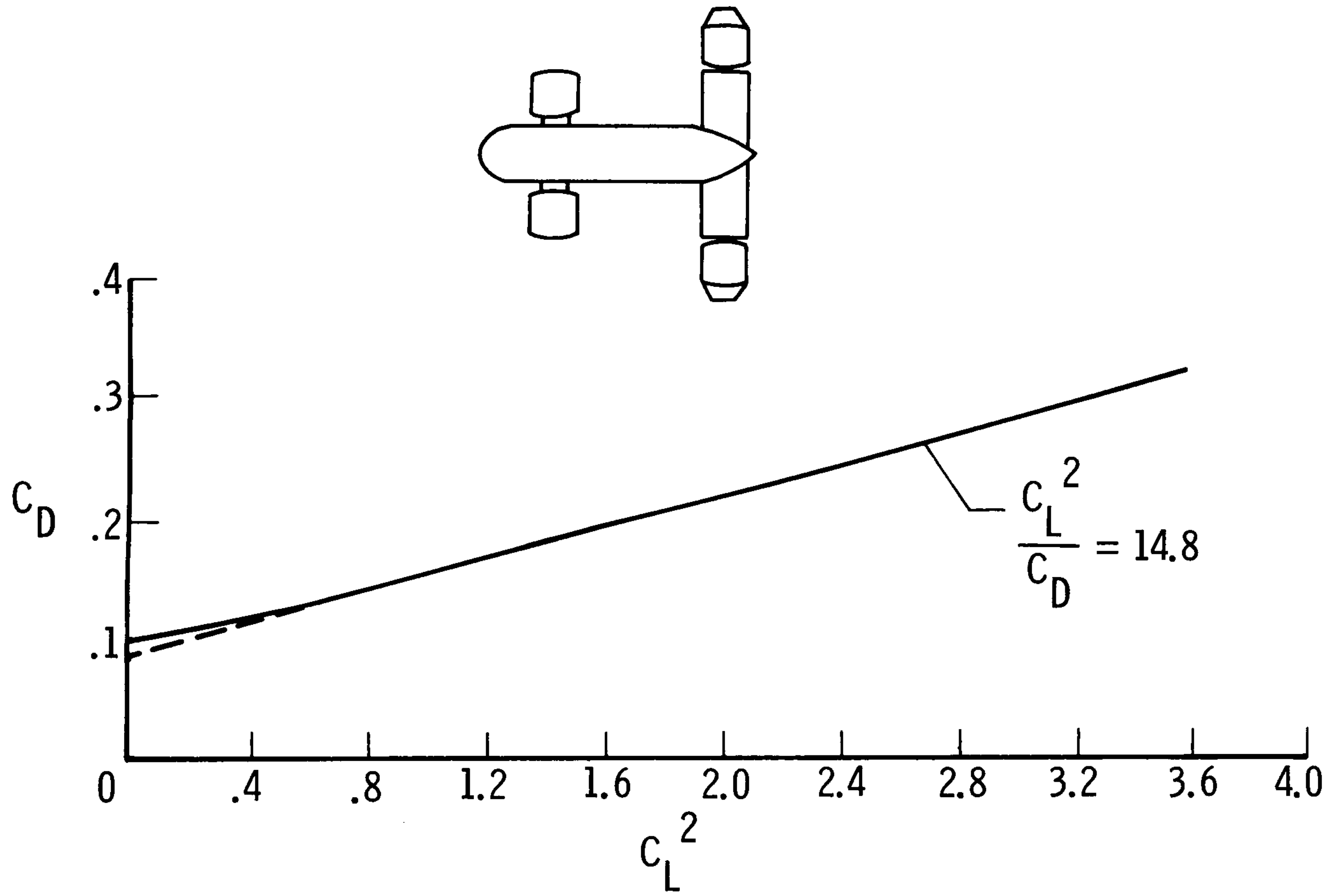

Figure 18.- Induced drag of tandem duct configuration.

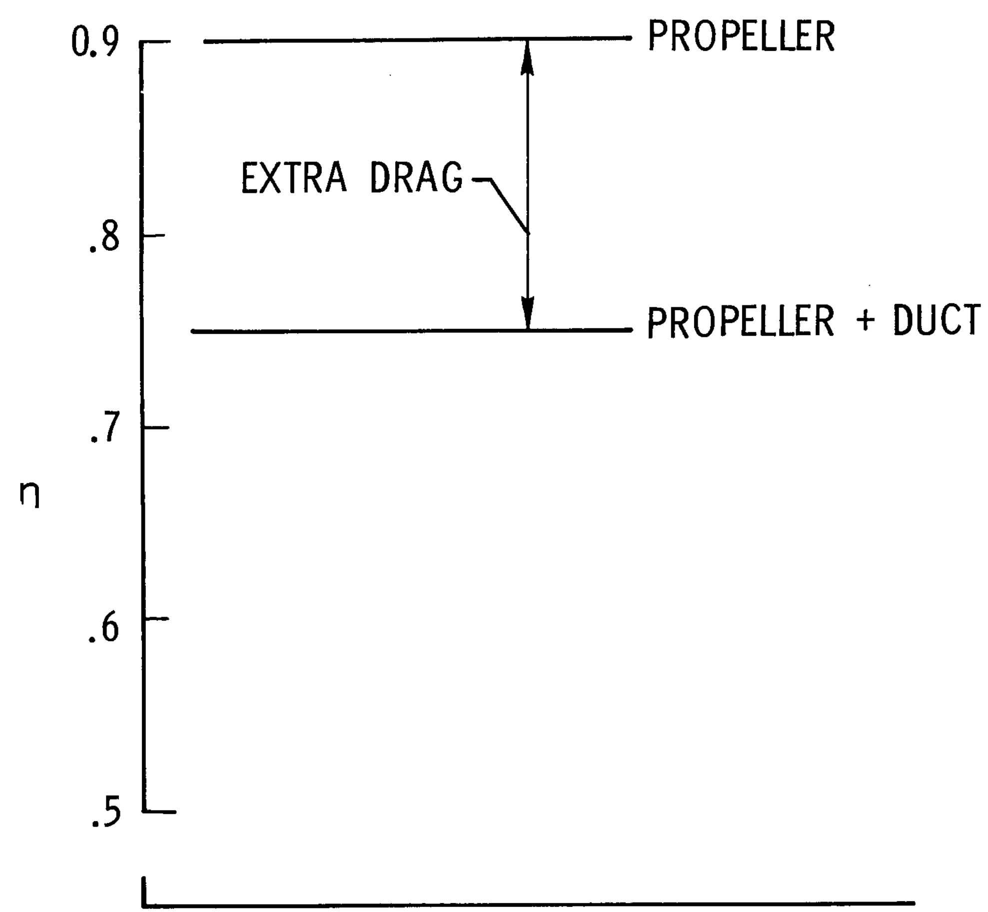

Figure 19.- Effect of additional duct drag on propulsive efficiency.

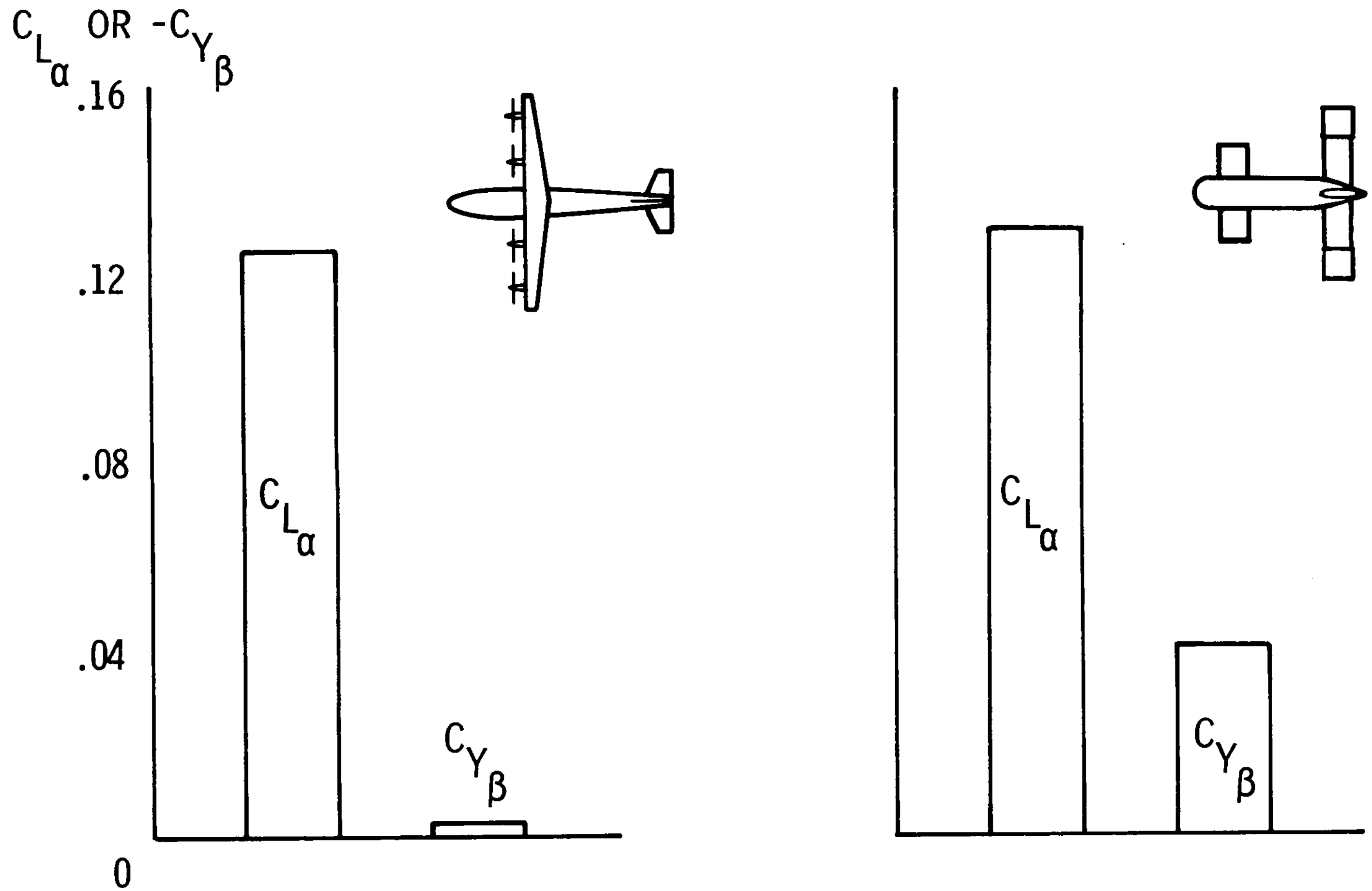

Figure 20.- Lateral force of tilt-duct configuration.

NASA-Langley, 1967